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TECHNICAL REPORT 1795
March 1999

Use of Perspective View Displays for Operational Tasks

M. St. John
Pacific Science and Engineering Group, Inc.

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

Research on when and how to use three-dimensional (3-D) perspective views on flat screens for military operational tasks such as air traffic control is confusing and contradictory. Considering the basic qualities and capabilities of two-dimensional (2-D) and 3-D views, we conducted two experiments. Because perspective views integrate all the dimensions, we hypothesized that 3-D views are better for object understanding. In contrast, we hypothesized that 2-D views are better for judging the relative position of objects because each dimension can be isolated. Participants viewed simple block shapes in 2-D or 3-D and either performed an object understanding task (e.g., identification, mental rotation) or a relative position task (e.g., directions and distances between objects). We found that a 3-D perspective view was far superior to 2-D views for understanding the shape of the simple blocks, but 2-D views were better than 3-D views for comprehending the relative position of two objects.

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INTRODUCTION

Many military operational tasks require the comprehension of three-dimensional (3-D) objects and environments. For example, the perception and understanding of a 3-D airspace are required for air route planning, fly and no-fly zones, terrain visualization, enemy targets, and enemy radar and air defense zones. Surface warfare officers have suggested that the display of tactical information in 3-D would aid in assessing the force structure of friends, neutrals, possible adversaries, and noncombatants (Kribs, Eddy, and Cowen, 1999). Consoles that display data in 3-D seem to provide a natural, and increasingly affordable, solution to these requirements.

Various 3-D display technologies are either available or under development. Some technologies involve the true representation of three dimensions in a holographic image (e.g., Lucente, 1997) or a volumetric display (e.g., Soltan et al., 1998). Most 3-D technologies, however, display a 3-D perspective view onto a flat surface such as a CRT or LCD panel. The image is two dimensional (2-D), but the viewing angle provides a 3-D perspective. For example, rather than displaying an environment from directly above (a planar or "bird's eye" view), perspective view technologies generally display the environment from a 30- or 45-degree angle. The user may also change the perspective to view any desired angle (Dennehy, Nesbitt and Sumey, 1994) or to view the image stereoscopically. However, most research evaluating 3-D displays has focused on performance when using stationary, monocular perspective views.

Many potential users who have viewed 3-D displays are positive about the displays' performance and use. However, Andre and Wickens (1995) caution system designers that sometimes "users want what's not best for them" and prefer to use systems that hinder rather than enhance their performance. Their review of studies on input devices, display interfaces, and color and 3-D rendered on flat screens provides evidence to support this hypothesis.

While it may be naively believed that more dimensions are always better, the evidence is decidedly mixed. Across an array of tasks, numerous studies have found benefits for 3-D perspective over 2-D (Ellis, McGreevy, and Hitchcock, 1987; Bemis, Leeds, and Winer, 1988; Burnett and Barfield, 1991; Wickens and Prevett, 1995; VanBreda and Veltman, 1998; Andre et al., 1991; Haskell and Wickens, 1993). Other studies have found rough parity (Wickens and May, 1994; Wickens et al., 1996), and still other studies have found 2-D superior to 3-D (Boyer and Wickens, 1994; Wickens et al., 1995; Boyer, et al., 1995; O'Brien and Wickens, 1997). The details of tasks and interfaces vary widely, and it seems likely that some results depend more on these details than on the nature of the displays themselves (e.g., Baumann, Blanksteen, and Dennehy, 1997).

Haskell and Wickens (1993, p. 104–105) propose that 3-D perspective view displays lead to better performance whenever the tasks to be performed using the display are integrated three-dimensionally or whenever the method of performing the task with the display bears a strong resemblance to a similar task performed without a display. For flight displays, this includes flight control and identifying and making integrated judgments regarding other aircraft. In these cases, the similarity of the display representation to the view in visual-contact flight overcomes possible disadvantages of the 3-D format. However, for tasks that require focused attention and that do not have a visual analog in flight, it may be advantageous to create separate planar displays.

Unfortunately, this theory fails to resolve the confusion of 2-D and 3-D display use because it is so difficult to predict which tasks require "focused attention" and which tasks "require integration across dimensions" (Haskell and Wickens, 1993, p. 90).

Despite the complex and confusing nature of current results, if we are to influence designs for the better, the time to do so is now. Industry is bringing advanced graphics to the marketplace for entry-

level personal computers, but these systems are designed without sufficient regard for usability. Commercial display vendors and software application designers agree that the window of opportunity for human-computer interaction (HCI) design guidance for 3-D displays is closing quickly (e.g., Brandenburg, 1996).

What are the benefits and liabilities of 3-D versus 2-D displays? We believe that the main advantage of 3-D perspective views is the capability to easily convey the shape of complex objects such as molecules. The appeal of 3-D displays may well stem from this capability. The main disadvantage of 3-D perspective views seems to be that the ambiguity and distortions associated with foreshortened angles and distances make precise judgments of distance and relative position difficult. Often, natural depth cues are available in a scene that can be used to compensate for the effects of foreshortening. When these cues are unavailable, however, the amount of distortion and ambiguity can be serious. For instance, in air traffic control, the aircraft are far away and small, so few depth cues are available, and it is quite difficult to determine their distances and relative positions. Which aircraft is furthest away? Which is highest? Is that balloon in the flight path?

To counteract problems associated with foreshortening, many display engineers have experimented with adding artificial depth cues to 3-D perspective views. For example, a common artificial cue is a "shadow" that lies on the ground directly underneath an object, such as an airplane. The distance between the object and its shadow conveys altitude, and the location of the shadow on the ground conveys position. One problem with shadows is that for aircraft at high altitudes, the shadow on the ground is far away from the aircraft and may appear disconnected. Another problem is that shadows double the number of objects that must be displayed, which adds clutter to the display.

While previous research has tended to concentrate on specific design features and particular applications, we believe that we may gain insight into the controversy surrounding 3-D technologies by focusing on the fundamentals of visual perception. We need to understand how the view of objects impacts different cognitive tasks. In this report, we propose a new theory of how objects are perceived on perspective view displays, the fundamental limitations of these displays, and how and when these limitations impact different cognitive/perceptual tasks.

Based on our observations of 3-D advantages and disadvantages, we propose a hypothesis to predict when 3-D perspective views would benefit or harm performance. A 3-D view is useful for understanding the general shape of complex 3-D objects because it integrates the three dimensions into a single view and provides natural depth cues such as perspective, shading, and occlusion. Three-dimensional views, however, impair our perception of the relative position of objects because of the ambiguity and distortions associated with foreshortened angles and distances. We performed two experiments to test this hypothesis.

EXPERIMENT 1: OBJECT UNDERSTANDING

In Experiment 1, we tested the hypothesis that a 3-D perspective view leads to better object understanding than a 2-D view. Our goal was to make the stimuli simple and generic in the hope that our results would apply to a wide variety of tasks and content domains. Consequently, we created simple 3-D block shapes composed of 10 to 16 cubes. These block shapes were rendered as a 3-D perspective view or as a set of 2-D views (see figure 1).

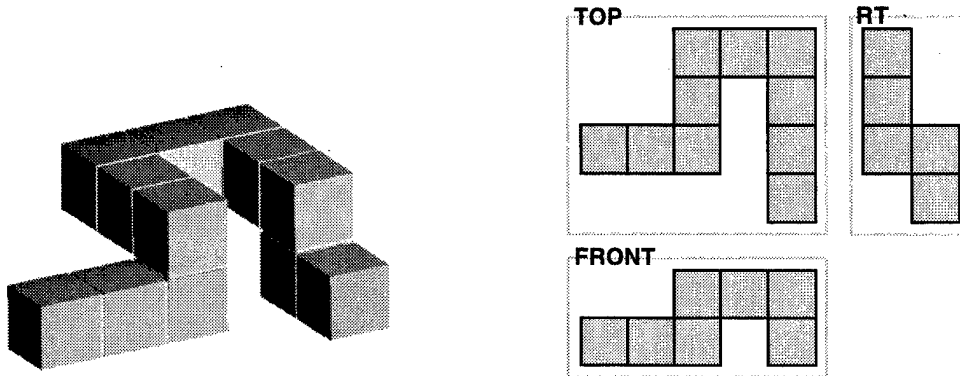


Figure 1. 3-D rendering of a typical block shape used in experiments (left side) and 2-D rendering of the same object (right side).

“Object understanding” was defined by four different identification-type tasks: (1) Identify 3-D, (2) Identify Real, (3) Identify Rotate-Yaw, and (4) Identify Rotate-Pitch. In the Identify-3-D task, participants were required to study one object, rendered in either 2-D or 3-D, and identify that same object from among a set of slightly different alternatives rendered in 3-D (see figure 2).

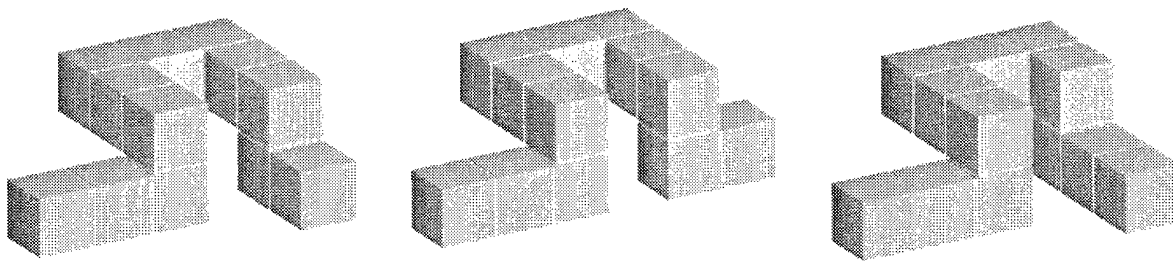


Figure 2. Three answer choices for the Identify-3-D task for the block shown in figure 1.

The 3-D renderings in the multiple-choice answer set provided an unfair advantage to the 3-D condition over the 2-D condition because in the 3-D condition, the correct answer looked exactly the same as the study block. To address this issue, we created a second task, the Identify-Real task, in which the answer sets were composed of wooden blocks. Participants still studied either 2-D or 3-D renderings, but they picked the correct answer from among three real blocks.

The third object understanding task was Identify Rotate-Yaw. This task required participants to study one block, rendered in either 2-D or 3-D, mentally rotate the block 90 degrees around the vertical axis and then identify the correct rotated block from among a set of slightly different alternatives rendered in 3-D (see figure 3). The fourth task was Rotate-Pitch. This task required participants to mentally rotate the study block 90 degrees around the horizontal axis and then identify the correct block from among three slightly different alternatives.

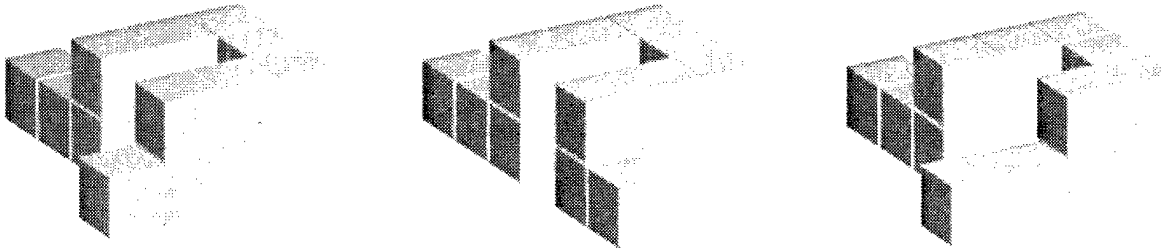


Figure 3. Three answer choices for the Rotate-Yaw task for the block shown in figure 1.

Mental rotation of an object requires “object understanding” because all of the object’s parts must be coordinated in the rotation. However, mental rotation is an inherently harder task than identification. Together, the relatively easy identification tasks and the relatively hard mental rotation tasks provided a good range of object understanding tasks.

METHOD

Participants

The participants were 32 Navy and civilian personnel employed at the Fleet Anti-Submarine Warfare Training Center, San Diego, California.

Stimuli

The stimuli were 10 2-D and 3-D renderings of simple block shapes created using a commercial off-the-shelf (COTS) graphical package and presented on a 15-inch liquid crystal display (LCD) panel. Each object was composed of 10 to 16 cubes arranged into a 3-D shape. Recognizable shapes were carefully avoided. For the 3-D renderings, a camera was positioned at 30 degrees above the horizontal plane of the object and at such an angle that three faces of the object were visible. In choosing the viewing angle, we carefully ensured that all prominent features of the object were visible. An omni-light and an ambient light illuminated the objects, and a single spotlight source above and 90 degrees to the right of the camera created shading. Shadows on the ground were not rendered. An orthographic perspective, rather than a vanishing point perspective, was used. Consequently, the objects appeared small and close to the participant. Figure 1 shows a 3-D block shape example. For the 2-D renderings, a top view, front view, and right side view of each object were created. The three views were labeled and arranged as shown in figure 1.

Procedure

For the Identify-3-D, Rotate-Yaw, and Rotate-Pitch tasks, a trial consisted of first viewing a single study object rendered in either 2-D or 3-D in the upper half of the screen. After 10 seconds, three multiple-choice answer objects appeared in the lower half of the screen while the study object

remained visible. The participant used a mouse to choose an answer object. Reaction times to complete each trial were recorded as well as errors. For each task, there were three practice trials (using simple objects) followed by 10 test trials.

In the Identify-Real task, the study object was displayed on the computer screen in the same place as the other tasks, but no objects were shown in the lower half of the screen. Instead, the participant was shown wooden blocks on a table to the left of the computer screen. For each trial, after a study object was shown for 10 seconds, a tone sounded and a screen was lifted to reveal the wooden answer blocks. The blocks were labeled “a,” “b,” and “c.” Participants chose the correct block by using the mouse to select an “a,” “b,” or “c” button on the computer screen.

Thirty-two participants were randomly assigned to one of the four conditions: (1) Identify 3-D, (2) Identify Real, (3) Identify Rotated Yaw, and (4) Identify Rotated-Pitch. Each participant received both the 2-D and 3-D condition for his or her assigned task. The subjects viewed the 10 stimuli only once for each condition (a total of two trials). The conditions were counterbalanced across participants. This experimental design allowed us to compare performance on the 2-D and 3-D condition of a task for each participant.

Before receiving the 2-D version of the task, participants were shown a video loop on the screen on how to interpret the 2-D renderings. The video showed a 3-D rendering of an object with the three 2-D views wrapped around the top, front, or sides of the object. As the video continued to play, the three views unwrapped, flattened out, and moved away from the object until the 3-D rendering and the 2-D rendering were side by side (see figure 4). The orientation of the three views was pointed out carefully. The video ran forwards and backwards for as long as the participant desired.

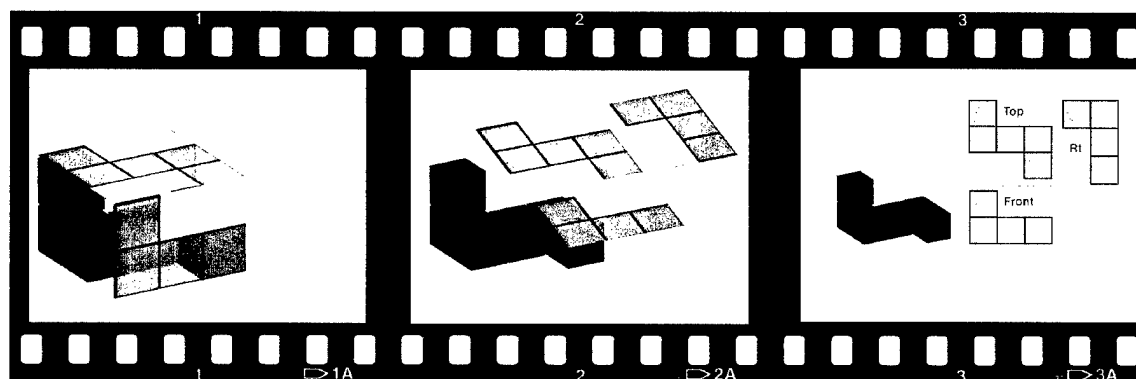


Figure 4. Three frames from the video clip shown to participants to explain the 2-D views.

RESULTS

For each participant, response times (RT) for correct trials were averaged, and a percent correct (PC) score was calculated. For each task ($n = 8$), the mean RT for the 2-D condition was compared to the mean RT for the 3-D condition (see figure 5). The mean percent correct scores also were compared. Participants were faster and more accurate with the 3-D views on the Identify-3-D task (RT: $t(7) = 7.25$, $p < .001$; PC: $t(7) = 4.58$, $p < .003$); and the Identify-Real task (RT: $t(7) = 3.52$, $p < .01$; PC: $t(7) = 2.18$, $p < .07$). Note that the mean differences between 2-D versus 3-D are about the same for both the wooden blocks and the 3-D graphic answer sets. This suggests that the benefits found for the 3-D graphic views are not because of the graphical similarity between the 3-D study stimuli and the 3-D answer stimuli, because the same benefits between the study and answer stimuli are found for the wooden blocks. Instead, the benefits must be because of the 3-D renderings are easier to understand

Participants were also faster and more accurate with the 3-D views on the Rotate-Yaw task (RT: $t(7) = 7.45$, $p < .001$; PC: $t(7) = 3.49$, $p < .01$), and on the Rotate-Pitch task (RT: $t(7) = 7.31$, $p < .001$; PC: $t(7) = 2.43$, $p < .05$).

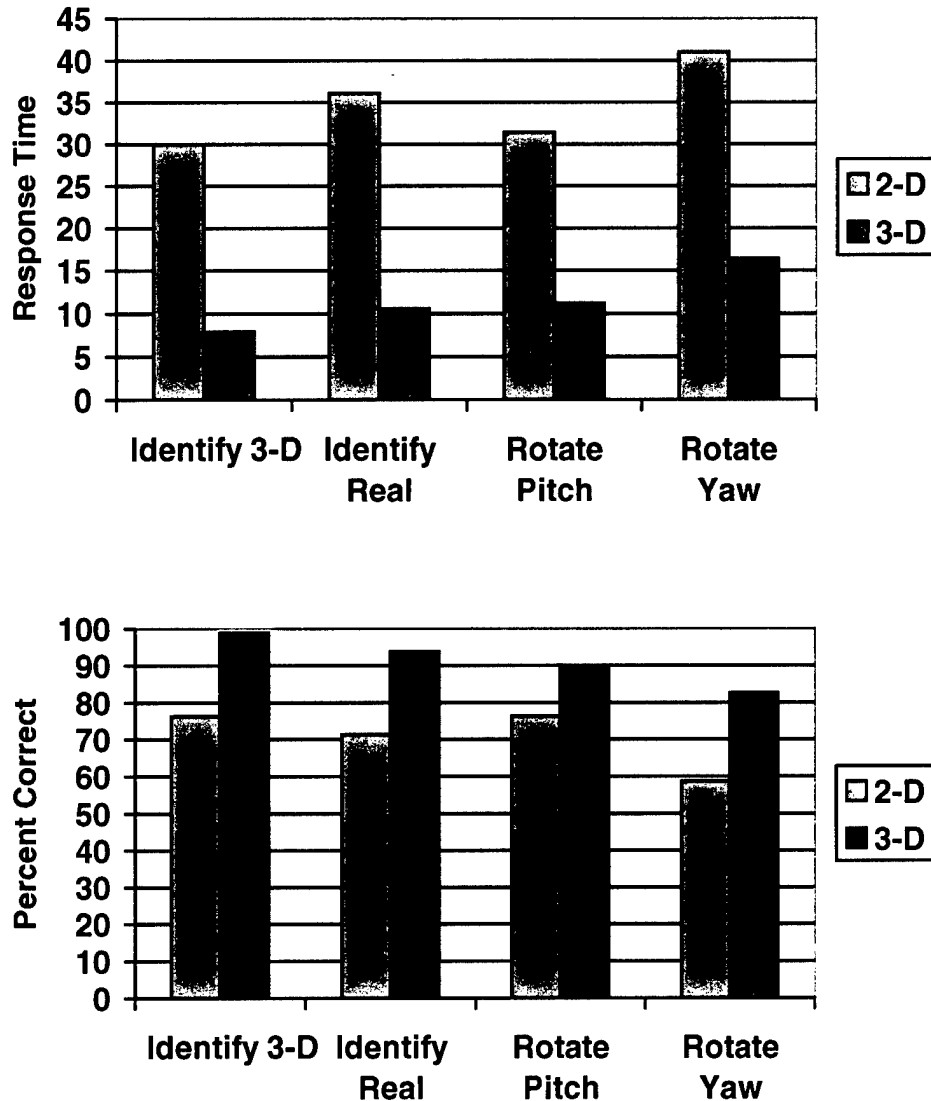


Figure 5. Mean response times (in seconds) and percent correct scores for the object understanding tasks.

DISCUSSION

The 3-D view is better for understanding the shapes of simple blocks. Participants, on average, seem to be about three times slower and about 10 percent less accurate on shape understanding tasks for 2-D views compared to 3-D views. The obvious weakness of the 2-D views for any of object understanding tasks is that the top-down, front, and side views must be integrated into a single object, which takes time. In the perspective drawings, by comparisons, the views are already integrated as a single object. Understanding the shape of the object is uncomplicated when all of the relevant object features are visible in the perspective view.

EXPERIMENT 2: RELATIVE POSITION

In experiment 2, we investigated the effectiveness of 2-D and 3-D views for determining the relative position of two objects. According to our hypothesis, the relative position of two objects should be easier to determine with 2-D views than 3-D views because the normalized viewing angles (e.g., top-down, side view) of 2-D views eliminate the foreshortening distortions found in 3-D perspective views. "Relative Position Understanding" was defined by three different tasks: (1) the Over-Same task, (2) the Over-Different task, and (3) the Navigation task.

In the Over-Same task, participants were presented with a 2-D or 3-D view that consisted of a simple block shape (cf., Experiment 1) and a ball the size of a single cube that was always located somewhere above the block. The participant's task was to determine which cube of the block was directly underneath the ball and to click on that cube using a mouse. From a single view in the 3-D condition (see figure 6), there is more than one correct location because the height and distance of the ball are ambiguous. This ambiguity derives from the very nature of the 3-D viewing angle: it cannot be determined whether the ball is high up and toward the front of the block or low down and toward the rear of the block. Consequently, we provided a second view of the block and ball from a different viewing angle to eliminate this ambiguity. Participants could compare the views to determine the height of the ball and determine which cube lay underneath the ball.

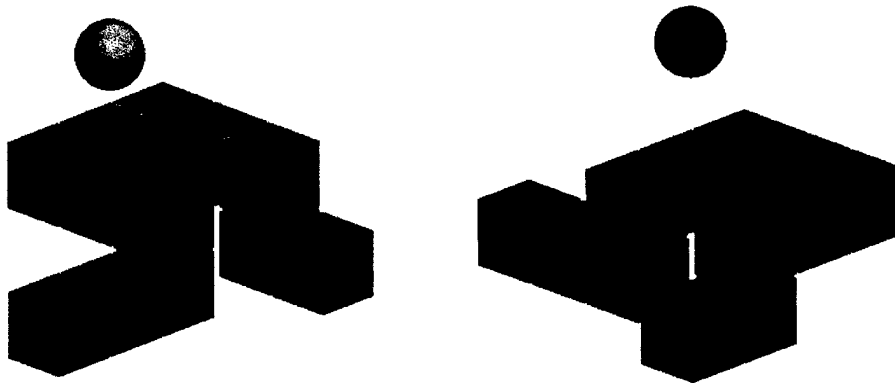


Figure 6. 3-D version of a typical block and ball used in the relative position task. Note that for each individual view, the location of the ball is ambiguous, but by comparing the two views, the location of the ball can be determined.

In the 2-D condition of the Over-Same task, the top-down, front, and side views of the block and ball were presented (see figure 7). The 2-D condition of the task should be very easy to perform because participants only need to look at the top view to determine which cube lies directly underneath the ball. In fact, if you click on the ball, you will click on the correct answer.

One might argue that this task is artificially easy, but we believe that it is simply the nature of 2-D normalized views, which make relative position tasks like this one simple and obvious. Nevertheless, we developed a second task, the Over-Different task, to address this issue. In the Over-Different task, participants were presented with 2-D or 3-D views of the block and the ball as described in the Over-Same task. Again, their task was to determine which cube was underneath the ball. However, this time, participants were presented in another window a 3-D view of the block with the ball removed.

Participants used this 3-D view of the block alone to report their answer. In Experiment 1, we found that a 3-D view was valuable in understanding object shape. Consequently, clicking on a cube in a 3-D view of the block was a better way to demonstrate understanding the location of the ball. Thus, in the 2-D condition of the task, participants simply could not find the ball in the top view and click on the ball to answer. Instead, they had to click on the correct cube in the 3-D view.

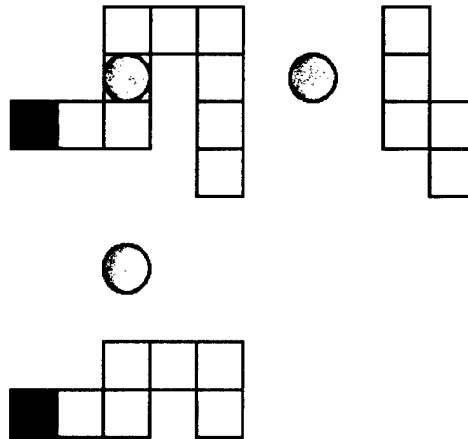


Figure 7. 2-D views of the block shape and ball in figure 5.

In the third task, Navigation, participants determined how to move from a designated cube (shown in red) in the block shape to reach the ball. The Navigation task immediately followed the Over-Same task for each stimulus trial. After clicking on the underneath cube, compass points appeared on the screen to indicate North, South, East, West, Up, and Down. Participants indicated the number of moves in “cubes” in each direction to move from the red cube to the ball. In the example shown in figures 6 and 7, you must move 3 up, 2 east, and 1 north to get from the red cube to the ball.

METHOD

Participants

The participants were 24 Navy and civilian personnel employed at the Fleet Anti-Submarine Warfare Training Center, San Diego, California. This experiment was conducted approximately 2 months after the completion of Experiment 1. About half of these subjects participated in Experiment 1.

Stimuli

For the relative position tasks, the stimuli were the same 10 simple block shapes used in Experiment 1 with the addition of a ball displayed somewhere above the block. The diameter of the ball was identical to the length of one of the cubes making up the block. The ball was located in empty space from one to three diameter-lengths above the block. The ball did not cast a shadow.

For the 3-D condition, two views of the block and ball were rendered. For each view, the camera was positioned at 30 degrees above the horizontal plane of the block and at 45 degrees to the left or right of the front view. Thus, for a single view, the location of the ball was ambiguous because the cubes underneath the ball line up along a diagonal of the block shape. The ball appears to be floating over each of the cubes along the diagonal. One cube was colored red for use in the Navigation task

described below. For the 2-D condition, a top view, front view, and right side view of the block and ball were rendered.

Procedure

On each trial, participants saw a block and ball configuration in either 2-D or 3-D. They first performed the Over-Same task by using the mouse to click on the cube directly underneath the ball. In the 2-D version, participants were informed that they could click on cubes in any of the three views, but that using the top view would be easiest. In the 3-D version, participants saw two views of the same block and ball configuration and were instructed to click on a cube in the block shape rendered on the right side of the screen. Immediate feedback was provided and the participant could not continue until the correct cube was identified. Total time to find the correct cube and first choice errors were recorded.

On each trial, immediately after answering in the Over-Same task, participants performed the Navigation task for that stimulus. Following a correct answer in the Over-Same task, a compass point icon appeared next to the block and direction menus appeared below the block. There were three separate direction menus: North/South, East/West, and Up/Down. When participants selected a direction menu, a pop up list of distances appeared on the screen. For example, when the North/South menu was selected, the list showed North 4, North 3, North 2, North 1, 0, South 1...South 4. After participants chose a distance, the menu would close and display the chosen distance for that dimension. After choosing distances along all three dimensions, participants clicked on a "submit" button. Their answer was evaluated and, if correct, the participant continued to the next trial. After three incorrect tries, the program moved on to the next trial and recorded a failure. Total time to select a correct answer was recorded. Additionally, we recorded first-try errors.

All participants received six practice trials on the Over-Same/Navigation tasks followed by 10 experimental trials. Half of the participants received the 2-D condition followed by the 3-D condition, and half of the participants received the reverse order. Next, half the participants were shown the 2-D condition of the Over-Different task and half were shown the 3-D conditions of the Over-Different task. Participants did not receive both conditions of the Over-Different task in an effort to keep participants from becoming too familiar with the stimuli.

RESULTS

Figure 8 shows mean response times and percent correct scores. For the Over-Same task ($n = 24$), participants were faster and more accurate using the 2-D views than the 3-D views (RT: $t(23) = 7.7$, $p < .0001$; PC: $t(23) = 6.0$, $p < .0001$). It is difficult to determine the relative position of two objects using the 3-D views. Any one view is ambiguous and two views of the block and ball must be compared to resolve relative position ambiguities. The 2-D views were found to be much more effective, but as previously mentioned, the top view of the block shape in the 2-D condition made the task very easy.

The Over-Different task was designed to remedy this complaint by requiring participants to respond by pointing to cubes in a separate 3-D view. Nonetheless, participants were still faster, though not reliably more accurate, using the 2-D rather than the 3-D display (RT: $t(22) = 2.9$, $p < .008$; PC: $t(22) = 1.3$, $p > .05$). The smaller effect size for this task compared to the Over-Same task was due, at least in part, to this task using a between-participants design.

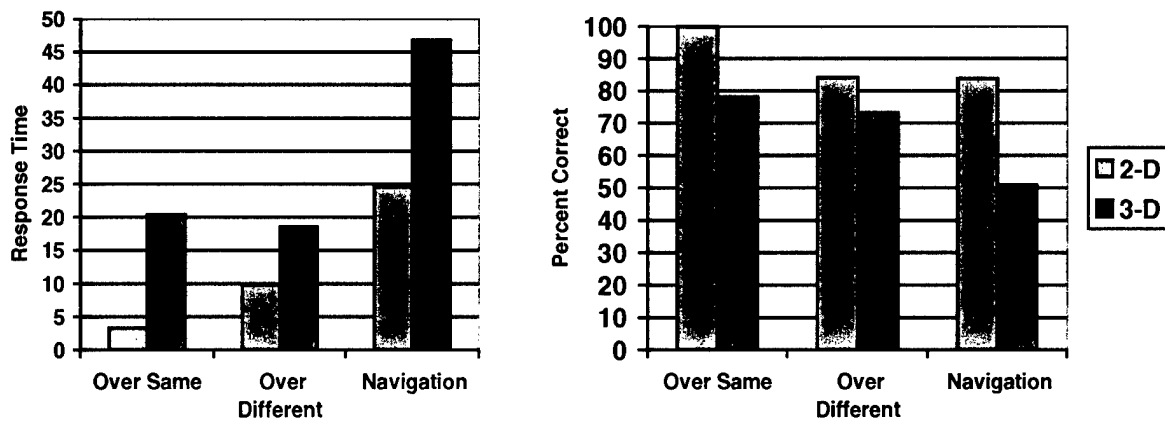


Figure 8. Mean response times (in seconds) and percent correct scores for relative position tasks.

Navigation task participants again performed faster and more accurately using the 2-D views than the 3-D views (RT: $t(23) = 7.3$, $p < .0001$; PC: $t(23) = 7.1$, $p < .0001$). What is interesting about the results from the navigation task is that the difficulties associated with the 3-D views are likely because of foreshortening distortions in the 3-D display rather than the ambiguity. Since the Navigation task directly followed the Over-Same task on each trial, participants had already resolved the ambiguity about the location of the ball. However, the foreshortening in the 3-D display distorts angles and distances, making them difficult to judge. Participants reported that height was especially difficult to judge because it required estimating distances across empty space.

DISCUSSION

How well can we discern the relative positions of multiple objects in the 3-D environment? For the Over tasks and the Navigation task, the 2-D display was superior to the 3-D display. For the Over tasks, the culprit was ambiguity in the 3-D perspective view. It is impossible to determine which cube lies directly underneath the ball in a single view. A second view from another angle, which is equally ambiguous, must be added, and then the two views must be compared to find the correct location. The 2-D views from the front and side are also ambiguous. However, the top view is entirely unambiguous for determining which cube is underneath the ball. In fact, the top 2-D view makes the task trivial: Find the ball and you have found the cube, too.

For the Navigation task, the culprit for the 3-D views is not the line-of-sight ambiguity, because the ambiguity is resolved in the Over-Same task. Instead, the culprit seems to be the distortion in the 3-D perspective view caused by foreshortening, which distorts the angles and distances between objects. In the 2-D views, there is no distortion of angles or distances. Instead, each dimension is presented faithfully. Consequently, it is easy to judge and move specific directions and distances along each dimension. To move in the dimension that is not represented, one simply has to turn to another view where that dimension is represented faithfully. Of course, to view another dimension requires a shift of the eyes and a re-orientation to the object or scene, but this perceptual shift does not seem to hinder performance as much as dealing with the distortions in the 3-D views.

GENERAL DISCUSSION

To summarize our findings, a single 3-D perspective view was far superior to three 2-D views for understanding the shape of the simple blocks used in Experiment 1. However, the 2-D views were far superior to two 3-D views for understanding the relative positions of two objects. We believe these results have profound implications for the design of visualization software from maps and geoplots to structural illustrations. The choice of 2-D or 3-D views, therefore, depends on the relative advantages and disadvantages of 3-D displays for conveying different types of information and which types of information a task requires.

There are three main advantages and two main disadvantages of using 3-D perspective views. The advantages are that 3-D perspective views (1) integrate all three dimensions into a single rendering, (2) can be enhanced with supplementary depth cues (e.g., shadows, shading), and (3) allow features of an object to be depicted that would be invisible in a normal 2-D view. The integration of all three dimensions into a single rendering is very useful for understanding shape. With 2-D views, no one view can provide information about all three dimensions of an object. To present a third dimension, a separate view must be added. For example, one view might show length and width but no depth. Another view would have to be added to show depth (and either width or length). Information about an object or scene must then be combined mentally, which is both difficult and time-consuming. A perspective view is easier to use because it integrates the dimensions in the view itself.

The second advantage of 3-D views is that extra depth cues can be added such as shadows, object scaling (i.e., distant object features are drawn smaller) and shading. Applied to a 3-D wire frame drawing, they make the 3-D shape of the object immediately apparent. Depth cues are difficult to add to 2-D views.

The third advantage of 3-D views is that they allow for the illustration of object features that would be hidden in a normalized 2-D view. Pockets and holes can be rendered with depth cues that would otherwise appear flat in one normalized view and invisible in others. In figure 9, the large pocket on top is more difficult to understand in 2-D than in 3-D and the small pocket in the notch is impossible to view from any normal 2-D angle. Further, the slanted cutout is indistinguishable from the notched cutout.

The two disadvantages of 3-D perspective views are the line-of-sight ambiguities and geometric distortions caused by foreshortening. Both of these disadvantages are exacerbated when the depicted scene is composed of small objects separated by empty space because there are few depth cues that can be used to compensate for the distortions. Because perspective views are oblique renderings, parallel lines are represented as converging lines. The perspective angle of the scene will affect our judgment of object shapes, slants, and distances. Right angles appear either acute or obtuse, and rectangles appear as trapezoids. As sides of an object approach the line of sight of the rendering, lengths shorten until they become entirely invisible, leading from distortion to complete ambiguity.

Directly along the line of sight, it is impossible to tell where an object resides. In a 2-D display, this line of sight ambiguity corresponds with the missing dimension. In a 3-D display, the line-of-sight ambiguity falls along all three dimensions along a vector in the scene beginning at any point on the screen's surface extending to the vanishing point in the scene. We believe that confining the ambiguity to a single dimension, while faithfully representing the other two dimensions, as in a 2-D display, is easier to think about and deal with than spreading the ambiguity across all three dimensions and representing none faithfully.

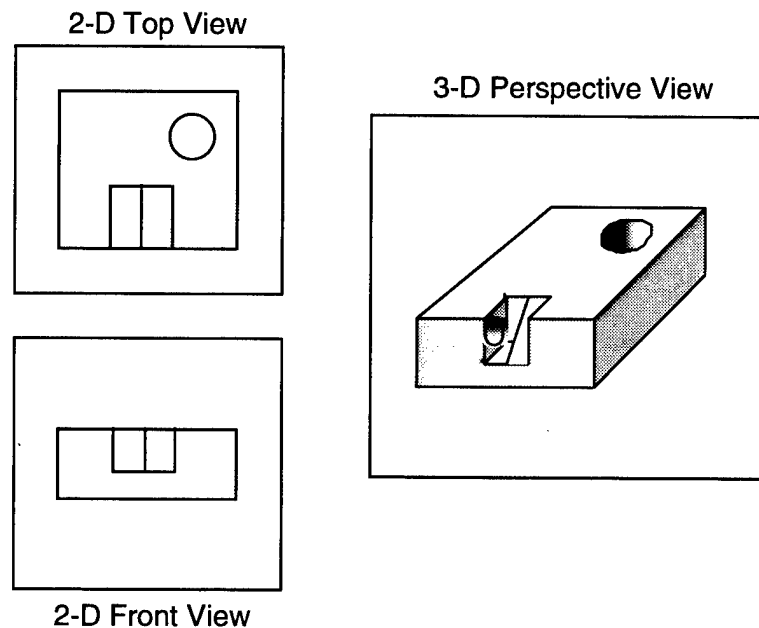


Figure 9. Top view, front view, and perspective view of block with cutouts and pockets.

The represented dimensions in the 2-D views are not distorted; what is visible is accurately represented. The user knows that scene ambiguities such as elevation in a plan view can be resolved by viewing the missing third dimension. This confinement of ambiguity to the dimension that is not represented provides better opportunities to deal with the ambiguity. A user can easily switch among a set of 2-D views to obtain undistorted information about each dimension of interest. In contrast, resolving scene ambiguities using multiple 3-D views requires substantial effort as demonstrated in Experiment 2.

Could the ambiguities associated with 3-D perspective views be reduced by adding additional natural depth cues to our stimuli, such as texture gradients, interposition, atmospheric perspective (in which the scene is viewed from above and at an angle, usually 45 degrees), shading, and brightness (Schmidt, 1997). A key issue is how well the available depth cues can be used in a scene. For a complex object or scene, many of these cues can be used effectively to convey depth. However, for a set of objects separated by empty space, such as aircraft approaching an airport or air corridors and missile routes over terrain, few depth cues can be used. Shading, texture gradients, and object scaling are all of limited value because they cannot be drawn on empty space, yet the critical relationships *between* the objects are defined by empty space. Since natural depth cues are unavailable for these situations, the ambiguity and distortions inherent with 3-D perspective views generally cannot be mitigated. Consequently, when the information of interest is the relationships among distinct objects, a 3-D perspective view can be seriously detrimental to accurate perception.

Finally, 3-D views may be less useful for understanding free-form objects such as terrain. For regular objects, it is relatively easy to compensate for the distortions introduced by a 3-D view. For example, the stimuli used in these experiments were composed of equal size cubes and right angles. The relationships among features of these objects are easy to understand because we know the true angles and distances. However, with free-form objects, we are generally unable to compensate for distortions caused by 3-D views. M. C. Escher took advantage of this idea in many of his drawings

by misapplying depth cues to create impossible figures. For example, in *Ascending and Descending*, Escher misrepresented angles and distances to create an infinite staircase that wraps into itself.

In future work, we plan to look more closely at the question of understanding the shapes of free-form objects such as mountain terrain or even blood vessels. Without regular distances and right angles to compensate for the distortions caused by foreshortening, the shapes of these free-form objects when viewed in 3-D may be difficult to discern with any precision. We speculate that there still may be some advantage for understanding the general layout of such objects in 3-D, but that this advantage will diminish, as more precise judgments are required.

Do more advanced 3-D display technologies, such as stereoscopic or volumetric displays, demonstrate the same limitations as 3-D views on flat screens? Both the artificial stereopsis of polarized lenses and the natural stereopsis of a true volumetric display add depth to a 3-D view. In a meaningful sense, objects that are further away are really further away. Ambiguity along the line of sight is reduced because each eye is offset and has a slightly different line of sight. However, distortions from foreshortening remain. Therefore, while it may be possible to use stereoscopic displays to marginally improve a rough sense of relative position, precision judgments will remain difficult. Therefore, tasks that require locating the positions of many objects in space, such as air traffic control or air warfare, will always benefit from the accurate representations found in 2-D views.

AN OPERATIONAL CONCEPT: ORIENT AND OPERATE

Our findings imply that combining both 2-D and 3-D views may prove optimal for use in operational military settings. The display interface would embrace a concept that we call "Orient and Operate." Users *orient* to the layout of a scene using a 3-D view, but then switch to 2-D views to interact with and *operate* on the scene. For example, in *Land Attack Warfare*, missiles are programmed to fly routes from launch platforms located off the coast to targets on land. These missiles, such as Tomahawks, are non-ballistic and have the capability to follow the terrain up, down, and around. In addition to following the terrain, the missile routes can be set to avoid anti-missile radar envelopes and other known obstacles, including designated air sortie corridors. Users often need to review and evaluate these routes to check for potential conflicts with new or prospective obstructions.

A 3-D view may work best to gain a basic grasp of the terrain, the shapes and locations of missile routes and obstacles (see figure 10). However, this display is too ambiguous and distorted for precise judgments. For example, in the 3-D view, it cannot be determined whether the yellow air corridor is next to or above the missile route shown in black. Also, the location of the ball could be resting on the plain or floating over the mountains, and the circular orange radar envelope appears oval.

Once a rough sense of the layout and the shapes of routes are obtained, a 2-D view may work best for achieving a precise grasp of relative positions and exact shapes. As another example, a user may have difficulty using a 3-D perspective view to effectively change a missile route to avoid a new radar envelop, but may find the same task easy using the 2-D view shown in figure 10. There are numerous design options to delineate this concept of Orient and Operate, such as presenting both 3-D and 2-D views simultaneously or allowing the user to select the viewing angles. The goal of our future work is to find the best interface design.

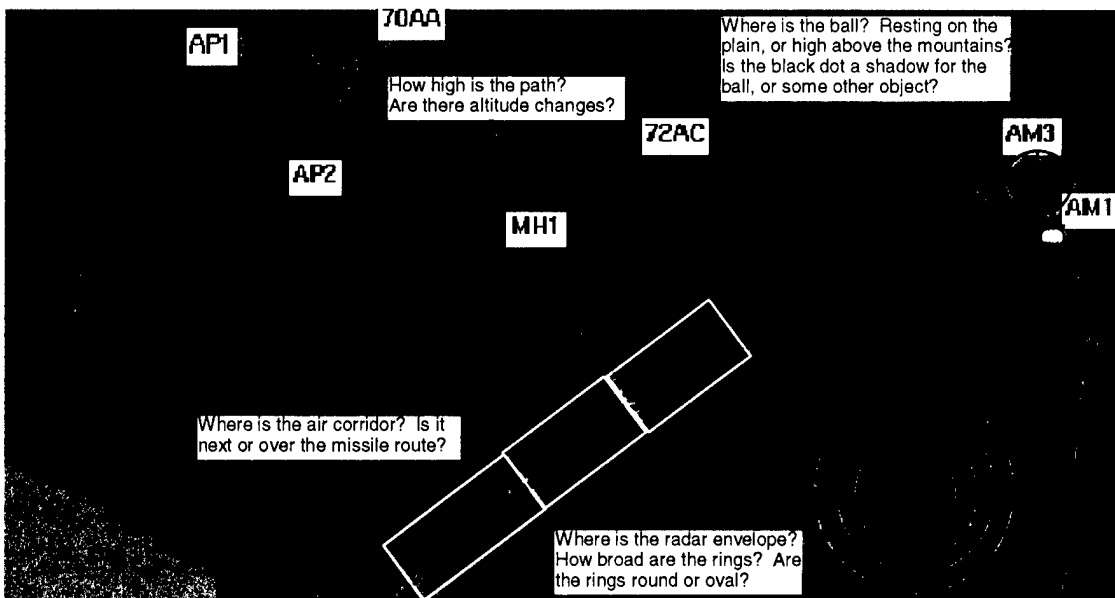
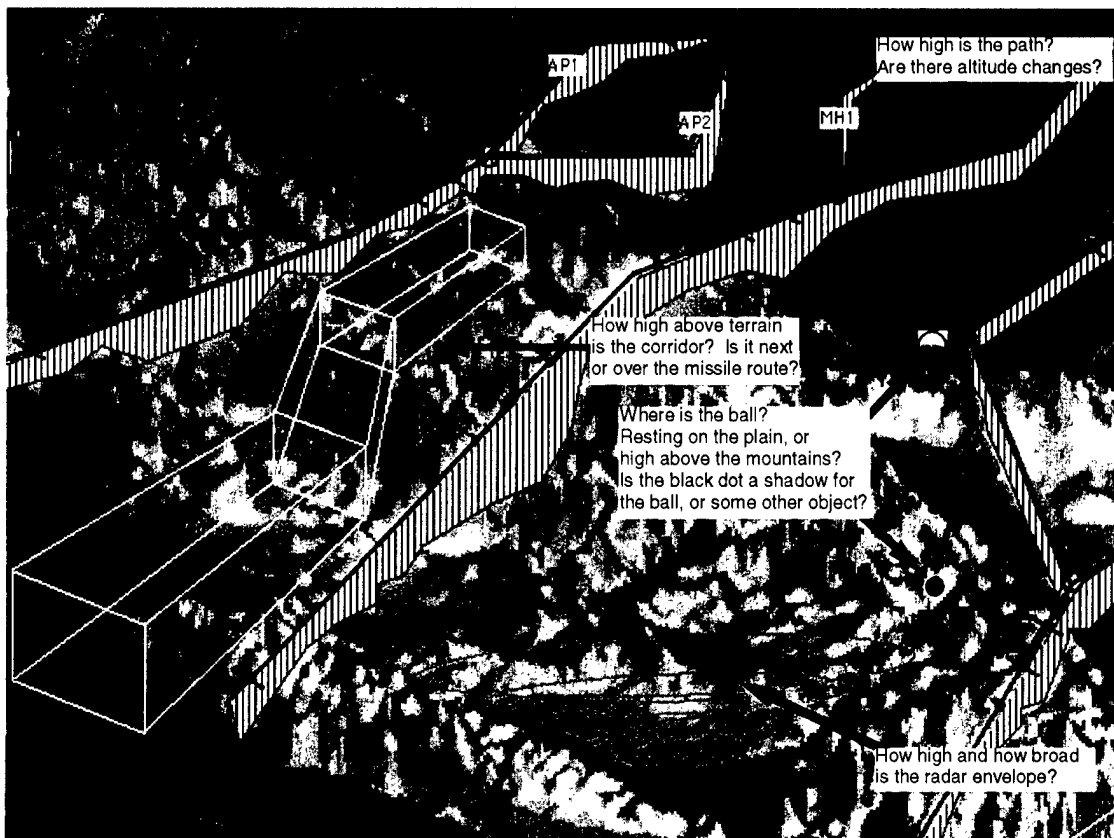


Figure 10. 3-D and 2-D examples of missile routes, terrain, and other obstacles.

In summary, we have found previous research to be confusing regarding potential benefits and limitations of 3-D displays. Our strategy has been to step back from more applied studies to consider the fundamental capabilities and limitations of 2-D and 3-D views, and ask what tasks best fit those capabilities. The compelling nature of 3-D views seems to reside in their integration of all three dimensions into a single view and their “natural” representation of space. Yet this natural representation is fraught with ambiguity and distortion. Using renderings of simple blocks, we found that each display can be useful (3-D for understanding shape and 2-D for understanding relative position). Finally, we recommend the Orient and Operate display design concept, which maximizes the benefits of each type of display (3-D for orientation to a scene and 2-D for precision and relational judgments). In future work, we plan to refine this concept by exploring ways to optimize 2-D and 3-D views using natural and artificial depth cues.

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